

**The Galaxy Cluster Luminosity-Temperature Relationship and  
Iron Abundances:  
A Measure of Formation History ?**

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## ABSTRACT

Both the X-ray luminosity-temperature (L-T) relationship and the iron abundance distribution of galaxy clusters show intrinsic dispersion. Using a large set of galaxy clusters with measured iron abundances we find a correlation between abundance and the relative deviation of a cluster from the mean L-T relationship. We argue that these observations can be explained by taking into account the range of cluster formation epochs expected within a hierarchical universe. The known relationship of cooling flow mass deposition rate to luminosity and temperature is also consistent with this explanation. From the observed cluster population we estimate that the oldest clusters formed at  $z \gtrsim 2$ .

We propose that the iron abundance of a galaxy cluster can provide a parameterization of its age and dynamical history.

*Subject headings:* galaxies:clusters:general - X-rays:galaxies:clusters - cosmology:observations

## 1. Introduction

The existence of an intrinsic spread or dispersion in the galaxy cluster X-ray luminosity-temperature (L-T) relationship has been noted by several authors (Edge & Stewart 1991, Fabian et al 1994, Mushotzky & Scharf 1997 etc.). Fabian et al. (1994) demonstrated a correlation between the amplitude of the L-T relationship and the cooling flow mass deposition rate  $\dot{M}(M_{\odot}\text{yr}^{-1})$  ( $L \propto T^{3.3}\dot{M}^{0.4}$ ).

Recently Mushotzky & Scharf (1997) have shown that the intrinsic dispersion of the L-T relationship does not seem to evolve and remains constant over a wide range in redshift ( $z = 0$  to  $z = 0.4$ ). Since the advent of high precision cluster metallicity measurements (Yamashita et al 1992) it is also clear that there is a dispersion of a factor of 2 in cluster Fe metallicities. This variation also does not evolve with redshift (Mushotzky & Loewenstein 1997). As Fabian et al (1994) have pointed out, it is likely that temperatures, iron abundances and cooling flows are all linked consequences of cluster histories.

In this paper we show that the variance in the L-T relationship and the cluster metallicity are correlated and can be explained in a simple model of hierarchical clustering if the dispersion in the present L-T relation reflects the *range* of cluster formation epochs. We propose that the range in cluster formation epochs can simultaneously help explain the correlation between the position of a cluster in the L-T relationship, its metallicity, and the correlations with cooling flow rates.

## 2. The L-T intrinsic dispersion

Using a large sample (102 total, 39 in the luminosity range  $45.2 \leq \log_{10} L_{bol}$  ( $\text{erg s}^{-1}$ )  $\leq 45.7$ ) of clusters we have previously demonstrated (Mushotzky & Scharf 1997) that both the mean cluster temperature and intrinsic temperature dispersion (at a fixed

bolometric luminosity) of the cluster population remains constant over the redshift range  $0.1 \lesssim z \lesssim 0.4$ . Using likelihood analysis we have estimated the intrinsic dispersion in the L-T relationship as  $\sigma_T \simeq 2$  keV at 7 keV, modeling the dispersion as a gaussian.

We shall show that this intrinsic dispersion can be plausibly explained as being largely due to a range of formation epochs in the cluster population and thus the data can place some constraints on these epochs. Semi-analytic models of the cluster population typically assume that the redshift of a cluster is approximately the redshift of its formation. In an  $\Omega = 1$  universe dominated by cold dark matter this is a justifiable simplification. It is not clear however that it should apply to lower density cosmologies or to those with (for example) a mixture of hot and cold dark matter. We use the formalism of Kityama & Suto (1997) who modify the Press-Schechter theory to include the epoch of cluster formation as an explicit variable. Kityama & Suto suggest that the following is approximately true, assuming a self similar model where the cluster core radius is proportional to the virial radius;

$$T \propto M^{2/3}(1+z_f)^\xi \left( \frac{1+z_f}{1+z} \right)^s \quad (1)$$

$$L_{bol} \propto M^{4/3}(1+z_f)^{\frac{7\xi}{2}} \left( \frac{1+z_f}{1+z} \right)^{\frac{s}{2}} \quad (2)$$

(c.f. Evrard & Henry 1991) and  $(z_f)$  is the cluster formation epoch and  $\xi$  is an effective index that is unity for  $\Omega = 1$  and no cosmological constant and varies weakly with  $z_f$  for low density cosmologies. A factor  $((1+z_f)/(1+z))^s$  relates the observed cluster temperature at redshift  $z$  to the virial temperature at  $z_f$ . Hydrodynamical simulations indicate that cluster temperatures are consistent with  $0 \lesssim s \lesssim 1$  (e.g. Navarro, Frenk & White 1995). Thus, at a given mass scale ( $M$ ), clusters which formed at earlier epochs are expected to be hotter and more luminous, with luminosity increasing more rapidly than temperature. Since the temperature evolution of clusters is seen to be zero or small (Mushotzky & Scharf 1997) we expect  $s \sim 0$ .

Preheating of the intracluster medium has been invoked (e.g. Kaiser 1991, Evrard & Henry 1991) to reproduce the apparent *negative* evolution seen in the luminosity function of the most luminous clusters at high redshift (Gioia et al 1990, Henry et al 1992), and to better fit the locally observed L-T relation with semi-analytic models. The assumptions made in such models (Kaiser 1991) imply that the heated gas will contract until the gas temperature is roughly equal to the virial temperature of the dark halo. The gas density profile is then set by the cluster potential rather than the dark matter density contrast. The effect on Equations 1 & 2 is that the overall  $z_f$  dependence of the L-T relation is weakened and therefore, for our purposes, this self-similar case provides a lower limit in the determination of an effective  $z_f$ .

Using the measured temperature dispersion at a fixed luminosity ( $\sigma_T \simeq 2$  keV at  $45.2 \leq \log_{10} L_{bol} \leq 45.7$ ), and assuming a fixed mass scale, we can then proceed to calculate the effective era of cluster formation. Combining Equations 1 & 2 and assuming that the observed  $\sigma_T$  is due to the range of formation epochs (from  $z_f^{min}$  to  $z_f^{max}$ ) we obtain;  $\log_{10}((1 + z_f^{max})/(1 + z_f^{min})) = \frac{4}{3\xi} \log_{10} \sigma_T$ , since  $s \sim 0$ .

For an  $\Omega_0 = 1$  ( $\lambda_o = 0$ ) universe ( $\xi = 1$ ) in which the most recent cluster formation is at  $z \sim 0$  then the earliest epoch of cluster formation would be at  $z \sim 1.5$  (with some at higher  $z$ , since we model the L-T dispersion as a gaussian). Since lower density cosmologies act to *increase* this upper bound we can make the general statement that, if clusters are still forming at  $z \sim 0$ , then they must have begun forming at  $z \geq 1.5$ . If the cluster population had essentially finished forming by  $z \sim 0.5$  then we would expect the earliest clusters to have formed at  $z \geq 2.5$ . Given the lack of observed evolution in the population of galaxy clusters to at least  $z \sim 0.3$  (e.g. Ebeling et al 1997) this latter result may be a better fit to observations.

### 3. Abundance Data

We have used a sample of 32 clusters ( $0.01 \lesssim z \lesssim 0.5$ ) with precise Fe abundance measurements (averaged over the cluster), temperatures and bolometric luminosities (Mushotzky & Loewenstein 1997, Yamashita et al 1992 and additional unpublished results) to determine if the Fe abundance is correlated with the relative deviation of a cluster from the mean L-T relationship.

In Figure 1 we have plotted the observed Fe abundance relative to solar (Anders & Grevesse 1989) as a function of the amplitude of the L-T loci, hereafter  $A_{LT}$ , assuming  $L \propto T^3$ , which has been determined to be a good empirical fit (Fabian et al 1994) as well as being close to theoretical expectations (which range from  $L \propto T^2$  to  $L \propto T^{3.5}$ ). The point size is proportional to the cluster temperature.

The x-coordinate,  $A_{LT}$ , is therefore a direct measure of the ‘sense’ of the dispersion from a single power law fit to the L-T relation. The larger  $A_{LT}$  is, the more luminous a cluster is for a given temperature. It is clear from Figure 1 that a correlation exists between iron abundance and  $A_{LT}$  such that clusters with higher abundances are more luminous at fixed temperature. The sole exception to this is the Centaurus cluster which is the second closest luminous cluster and is known to have a strong abundance gradient (Fukazawa et al 1994) and might therefore be considered anomalous. A Spearman rank-order correlation test on the data (with the Centaurus metallicity adjusted as indicated in Figure 1) confirms that Fe and  $A_{LT}$  are positively correlated with 98% confidence and  $r_s = 0.43$ . An unweighted least squares fit (plotted in Figure 1) yields:  $Fe \simeq 2.7 \times 10^{-8} A_{LT}^{0.16}$ . A maximum likelihood analysis of the iron abundance residuals to this best fit allows us to constrain the intrinsic dispersion (independent of  $A_{LT}$ ) in Fe to be  $\leq 0.1$  (90% confidence). The cluster A2218, with the lowest abundance in the sample, has been extensively studied (e.g. Squires et al 1996) and is generally thought to be in an unrelaxed dynamical state due to a recent large

merger. There is no apparent correlation with cluster temperature in the Fe- $A_{LT}$  plane. In Figure 2 the same data are plotted, but with point size proportional to redshift, no redshift correlation is seen in the Fe- $A_{LT}$  plane.

#### 4. Discussion

From Equations 1 & 2 the quantity  $A_{LT}$  should increase with earlier cluster formation epoch and thus we are led to interpret the data in Figure 1 to mean that higher abundance clusters formed earlier. This has profound implications for the nature of their formation.

The metallicities observed in clusters are thought to have originated primarily from SNe type II in an early epoch of star formation (Loewenstein & Mushotzky 1996). In this interpretation the intracluster medium will have undergone a significant ‘pre-heating’ at  $z > 1$  due to the energetics required to match the observed abundances. Pre-heating is also favoured by recent measurements of negligible, or slightly negative, cluster luminosity evolution to  $z \sim 0.3$  (e.g. Ebeling et al 1997, Jones et al 1997) and by measurements of negligible temperature evolution (e.g. Mushotzky & Scharf 1997). Recent semi-analytical models of galaxy formation (Kauffmann & Charlot 1997) indicate that 80% of the intracluster metals were produced at  $z > 1$ .

The sense of the relationship between  $A_{LT}$  and abundance to  $z_f$  can be expressed in terms of a hierarchical ‘tree’ history. In such a theory there are two extremes. Either clusters have started as a single, dominant potential well, into which much smaller clumps have fallen, or clusters have formed by the merger of intermediate sized clumps over their history. These two routes to a final cluster are, in fact, seen explicitly in halo merger studies (e.g. Lacey & Cole 1993, Huss, Jain & Steinmetz 1997). We note that, for either case, the rate of growth of the progenitor mass is generally slower for low density cosmologies (Huss,

Jain & Steinmetz 1997).

In the pre-heating scenario it is expected that low mass sub-clumps will, because of their smaller potential wells, lose a substantial fraction of their heated enriched gas during the epoch of metal formation while massive systems will not. Thus a cluster formed later, whose evolution is dominated by the merging of smaller sub-clumps, will tend to have a lower metal abundance and a lower value of  $A_{LT}$  than a massive system formed earlier by the collapse of a single large overdensity. This explanation does however assume that clusters formed through these two routes have roughly the same final virial mass. In hierarchical models the most massive systems are expected to form last so clearly this ‘direct’ interpretation of the L-T dispersion is a likely oversimplification of the real play-off between system mass and  $z_f$  in Equations 1 & 2.

Observational evidence (e.g. Davis 1995) indicates that (where discernable) the subclumps involved in the formation of luminous clusters at low redshift are themselves typically low luminosity systems, such as groups. The abundances measured in groups are indeed often low (Fukazawa et al 1996), consistent with our hypothesis.

Our interpretation of the correlation in Figure 1 is also consistent with the results of Fabian et al (1994) which demonstrated that higher  $\dot{M}$  clusters have larger  $A_{LT}$  and that higher  $\dot{M}$  clusters typically have higher abundances. Cooling flows are expected to be disrupted by major mergers and hence objects which have not experienced mergers are relatively undisturbed and, in the language used above, are ‘truly’ old. They would then also be expected to have higher  $\dot{M}$ ’s. One of the ‘oldest’ objects in our sample would then be 2A0335+096 (Figures 1 & 2). There is evidence (Irwin & Sarazin 1995) that this cluster is indeed at a late stage of cooling, which places its age at  $\gtrsim 4\text{Gyr}$  (Christodoulou & Sarazin 1996, and Hu 1988), or a  $z_f$  of  $\sim 2$ , consistent with the results in Section 2.

It is important to note that the definitions of formation epochs (in terms of mass halos)



are actually somewhat arbitrary, for example Lacey & Cole (1993) propose a criteria that  $z_f$  is the epoch at which a halo of mass  $M$  at  $z$  had a mass greater than  $M/2$  for the first time. Thus, the above scenario is certainly overly simplistic and it is probably better to consider cluster formation as a continuous process which, however, for illustrative purposes can be subdivided into general classes such as the two (realistic) extremes described above.

Clearly, the range of abundances combined with the L-T dispersion results shown above, should allow, through careful modeling, new constraints to be placed on the overall pathways of hierarchical cluster formation.

## 5. Conclusion

We propose that the observed dispersion in the cluster L-T relationship reflects the range in cluster formation epochs within a hierarchical universe. The relationship of cooling flow mass deposition with luminosity and temperature is then qualitatively explained if we assume that cooling flow clusters are both initially denser and older than non-cooling flow clusters, which we associate with recent major mergers. The observed dispersion in cluster iron abundances and its correlation with position in the L-T diagram ( $A_{LT}$ ) is accounted for (except for a possible residual intrinsic dispersion of  $\Delta Fe \leq 0.1$ ) if the smaller mass units that are involved in the mergers can lose metals via an early cluster wind phase and then merge to form the lower  $A_{LT}$  systems. In this scenario we can constrain the earliest cluster formation to be at  $z_f \gtrsim 2$ . While there are clearly other candidate mechanisms for producing the observed variances in abundances and temperatures (e.g. inhomogeneity of the intracluster medium (Fabian et al 1994), these must ultimately also be functions of the cluster age and history.

Larger data sets and more detailed cosmological simulations will greatly improve

our understanding of the results presented here and will test our hypothesis that the measurement of a clusters iron abundance informs us of its age and formation history. For example, we expect that higher abundance clusters will typically have higher baryonic fractions. We also expect that the most massive clusters observed at  $z \simeq 1 - 2$  will typically have higher abundances than their local counterparts. In future work we will investigate these predictions.

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Fig. 1.— Measured iron abundance (open circles) is plotted against  $L/(T^3)$  (as the logarithm), the amplitude of the L-T power law required for a given cluster:  $A_{LT}$ . Circle size is linearly proportional to cluster temperature. The solid line is an unweighted least squares fit to the data and indicates the sense of the proposed abundance relationship. Virgo, Centaurus, A2218, A1060, A1204 and 2A0335+096 are labelled. The Centaurus cluster Fe abundance (from Ginga) is considered anomalous due to strong abundance gradients, the vertical arrow indicates the correction obtained by going from emission measure weighted abundance to average abundance.

Fig. 2.— As for Figure 1, but point size is now linearly proportional to cluster redshift



